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Strength and Durability of Concrete

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Strength and Durability of Concrete

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Abstract:	This investigation examined variables influencing the compressive strength and salt scaling loss of concrete and devised a method for predicting the quality of concrete. The work was mainly focused on 28-day strength and 50-cycle salt scaling loss of concrete. Statistical analyses were performed on test data consisting of chemical and physical properties of cements; properties of fresh concretes; compressive strength, salt scaling loss, and air void parameters of mature concretes. For the test data studied, results from the correlation analysis indicated that there was not a consistent set of variables correlated to the strength or salt scaling loss for different types of concrete. In the case of salt scaling loss, cement particles of 20 micron or finer had a strong correlation. The variables identified in the correlation analysis were analysed and equations predicting strength and durability of concrete were developed using multiple linear regression. Discriminant analysis appeared to be a promising method for predicting the quality of concrete.
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EXECUTIVE SUMMARY

This report presents the findings of a statistical analysis undertaken to identify the factors responsible for the observed variation in the quality of concrete specimens. A secondary task was to propose a technique that could be used as a test for predicting the quality of concrete.

It must be emphasised that the experimental investigation, on which this report is based, was designed to examine the influence of different cements on the strength and durability of concrete. Traditional factors such as cement content and water/cement ratio were not intended to be variables. These two factors have a profound influence on the strength and durability of concretes made from a single cement. The concretes compared in this experiment all used the same aggregate, had the same cement content and had virtually the same water/cement ratio. This was done to minimize these influences, so that the effect of the cements per se could be studied.

The data used in the analysis were the results of measurements made on eighteen different type 10 cements, and also on concrete samples made from each of the cements. Two different aggregates were used in preparing the concretes, a good quality aggregate (designated A) and an inferior aggregate (designated B). In addition, for each aggregate, mixes were designed to produce concrete samples with nominal strengths of 20 MPa or 30 MPa. Thus each cement was used to produce four types of concrete. This summary will concentrate on the 30 MPa concretes.

The data consisted of the chemical and physical properties of the cements, the properties of the fresh concretes, plus the compressive strength, salt scaling loss and air void parameters of the mature concretes. In all, some 111 properties were measured by the Concrete Section of the Engineering Materials Office of MTO.

Concrete quality cannot be measured directly; therefore, the 28 day compressive strength and the 50 cycle salt scaling loss were used as surrogates. Correlation analysis was used to identify which properties of the cements had a strong association with either of these variables. The first important result was that there was not a consistent set of variables correlated to the strength or the salt scaling for all the concrete types. In the case of the 30 MPa concretes the variables common to both the A and B cases were established.

Particular attention was paid to the results of the grading curve for the cements. It was found that in the case of the 50 cycle salt scaling loss a consistent pattern of behavior was evident. Firstly, the percentage of very fine particles (less than 2 micron) in the cement had a strong positive correlation. Secondly, the percentage of particles in the range 2-20 micron had a very strong negative correlation - much stronger than the more commonly used percentage passing 45 micron criteria. Thus cements producing concrete with superior salt scaling durability had a relatively large percentage of particles in the 2-20 micron range.

In order to establish relationships that could be used to predict the strength or durability of concrete, the variables identified in the previous exercise were analyzed using multiple linear regression and the best fit equations developed. These equations provide a good fit to the data given the small number of samples in the data set. Given this success, it is anticipated that a larger data set would allow the development of more precise models. It may also be necessary to investigate the effect of the aggregate on the properties of the concretes.

The second objective of this research was examined using another statistical technique called discriminant analysis. This methodology was used to develop an equation that

will differentiate between 'good' and 'poor' concrete in terms of the properties of the cements. The equation for the 30B concretes worked extremely well, assigning all the cases correctly. The variables included in the equation were: free calcium oxide, ferric oxide, silicon dioxide, alkali content, effective water-cement ratio and the proportion of cement between 2-20 micron. This technique shows good potential as a quality acceptance criteria.

A tentative engineering explanation of the influence of the cement manufacturing process on the important cement properties identified by the statistical analysis is included in the report.

1. INTRODUCTION

For some time concern has been expressed that the quality of the concrete used in Ontario has shown considerable variation, even though all the cements used meet the OPSS Form 1301 (CSA standard CAN 3-A5-M83) requirements for type 10 cements.

To investigate this concern, an experiment was devised, by the Concrete Section of the Engineering Materials Office, whereby the physical and chemical properties of eighteen available cements were measured. These cements were then used to produce samples of concrete with nominal compressive strengths of 20 and 30 MPa respectively. Within each of these strength categories two types of coarse aggregate were used in the mix, a crushed dolomite limestone called 'A' and a partially crushed natural gravel called 'B'. Various properties of these four resulting concrete types (20A, 20B, 30A, 30B) were also measured.

It must be emphasised that the experimental investigation, on which this report is based, was designed to examine the influence of different cements on the strength and durability of concrete. Traditional factors such as cement content and water/cement ratio were not intended to be variables. These two factors have a profound influence on the strength and durability of concretes made from a single cement. The concretes compared in this experiment all used the same aggregate, had the same cement content and had virtually the same water/cement ratio. This was done to minimize these influences. so that the effect of the cements per se could be studied.

The major objective of the work undertaken for this report was to use statistical techniques to identify the factors responsible for the observed variations in the quality of the concrete specimens. A secondary objective was to devise a method for predicting the quality of a concrete.

Following discussions with MTO personnel it was decided that the quality of the concrete should be assessed in terms of the compressive strength of the concrete (CSA standard A23.2-3C, 9C) and also the cumulative mass loss (mass of material lost from surface) in a salt scaling test (ASTM C672-84 using 3% sodium chloride solution as the de-icer). Strength was measured at 3, 7, 28 and 91 days, and salt scaling loss at 5, 10, 15, 25 and 50 cycles. In particular it was decided that the 28 day compressive strength and the 50 cycle salt scaling loss would be the most appropriate variables to use.

Therefore, for the purposes of this analysis, these two variables (for each of the types of concrete) were considered to be the dependent variables. The analysis attempted to predict the value of these eight dependent variables in terms of the other (so called) independent variables.

2. THE DATA FILES AND CODING

The MTO data were in the form of 12 tables labelled A through L. Except where stated otherwise, each data point was the result of a single measurement of that variable. The contents of the tables were as follows.

2.1 Table A

Table A was an identification key to the eighteen type 10 cements included in the experiment.

2.2 Table B

Table B contained the results of the thirteen physical tests performed on the cements. The specific variables measured and their identification code are shown in table 1.

Where a particular attribute was measured by more than one technique, only one of the measurements was retained for further analysis. This was done because the results from the alternative test methods were highly correlated. In all cases the results of the MTO method were retained. The variables dropped from further analysis are identified in table 1 by an asterisk.

2.3 Table C

Table C contained the grading curves for the cements. The original 13 variables showed the percent passing specified sieve sizes. Considerable thought was given to the best use for these data. It was decided to augment these data by calculating the percentage of cement between two sieve sizes, that was passing the larger sieve but retained by the smaller. This resulted in 42 more variables. It should be noted that because the data are highly correlated only one or two were used in any models that were developed. Finally it was decided to include the total specific area of the cements as a variable. This variable was included because its calculation made use of all the data in the grading curve. The variables measured and their identification code are shown in table 2.

2.4 Table D

Table D contained the results of nineteen chemical tests performed on the cements. As in the case of table B, whenever a variable was measured by more than one technique the result of the MTO method was retained for further analysis. In addition, the data were used to calculate three more variables (the percentage of C_3S , C_2S, and C_4AF) thought to be of relevance. The specific variables measured and their identification code are shown in table 3.

2.5 Table E

Table E contained details of the physical properties of the two coarse aggregates (A and B) used in the preparation of the concrete samples. No details are included in this report because these data were not included in the list of variables to be analyzed.

2.6 Table F

Table F contained details of the mix proportions used in the preparation of the four types of concrete (20A, 20B, 30A, 30B) along with the results of tests on the fresh concrete. The variables measured and their identification code are shown in table 4.

No samples of concrete using aggregate A were made from cements #13 and #14. Similarly no samples of concrete using aggregate B were made for cement #5.

2.7 Table G

Table G contained the compressive strength for each of the types of concrete. Each entry in the table was the average from the testing of four cylinders. The individual results

for each cylinder were given in table K. The variables measured and their identification code are shown in table 5.

2.8 Table H

Each of the 20 MPa concrete samples was subjected to a freeze/thaw test as specified in ASTM C666-84. After discussion with MTO it was decided not to include these data in the detailed analysis.

2.9 Table I

Table I contained results of the cumulative mass loss on samples of each of the concretes for a salt scaling test similar to that described in ASTM C672-84. Each result was the average of tests on two samples. Details of the individual test results were given in table L. The variables measured and their identification code are shown in table 6.

2.10 Table J

Table J contained the results of a measurement of air void system parameters. These were obtained from a linear traverse of the samples according to ASTM C457-82a. Of the 22 variables measured many were excluded from further analysis. In particular only the 'Total' for each of the variables in the linear traverse were retained. Some of the other variables that were listed were duplicates of measurements in other tables. The specific variables measured and their identification code are shown in table 7.

After this initial review of the MTO data 111 variables were retained for further analysis.

3. CORRELATION ANALYSIS AND INFLUENCE CHARTS

The basic step in developing causal models, that can be used to predict concrete quality, is to identify the degree of association between the dependent variables and the independent variables. This was done on the basis of the measured values of the variables and not on the basis of preconceived knowledge of the properties of concrete.

The SYSTAT (SYSTAT INC. Evanston IL 1986) package of statistical programs was used to analyze the data. The Pearson Correlation Coefficient provides a measure of the inter-relationships between pairs of variables. A correlation coefficient close to +1 (or -1) indicates a strong association with a positive (or negative) relationship. A coefficient close to zero indicates little or no association between the pair of variables.

On the basis of the calculated correlation coefficient, between the dependent variables and each of the independent variables, each independent variable was classified as:

1. potentially important
2. possibly important
3. not important

The rules for making this classification were as follows:

1. Correlation coefficient between -1.0 and -0.4 or +0.4 and +1.0
2. Correlation coefficient between -0.4 and -0.2 or +0.2 and +0.4
3. Correlation coefficient between -0.2 and +0.2

The first break point (of ± 0.4) for making a decision is based on the fact that the 95% confidence level for the correlation coefficient of 18 pairs of observations is ± 0.44 . The second break point of ± 0.2 is arbitrary. Initially the correlation coefficients were calculated between the eight dependent variables and each independent variable retained for analysis.

Table 8 shows which variables are potentially important for the 28 day strength and the 50 cycle salt scaling loss for each of the four concrete types. The number associated with each variable is the calculated correlation coefficient.

Table 9 shows which variables are possibly important for the 28 day strength and the 50 cycle salt scaling loss for each of the four concrete types. The number associated with each variable is the calculated correlation coefficient.

Table 10 lists the variables that were found to be unimportant.

It should be noted that a low correlation coefficient value in the tables indicates only that the linear relationship between variables is small; other relationship, such as nonlinear correlation, may exist. Because of the scatter in these data it was not possible to postulate nonlinear relationships.

The independent variables, that were found to be potentially important, were analyzed to detect any cross correlation between them. This was necessary because a good causal model should not contain closely related variables.

3.1 The Grading Curve Data

The fifty-six variables derived from the grading curve data were treated separately because of their strong inter-relationships. For each dependent variable, plots were made showing the range of particle size under consideration labelled with the corresponding correlation coefficient. From a visual inspection of these plots an important representative variable was selected for inclusion in the modelling process.

A consistent pattern emerged in these plots. The 28 day strength had few or no strong correlations. The salt scaling on the other hand exhibited two common features. Firstly the percentage of very fine particles (less than 2 micron) had a strong positive correlation. Secondly the percentage of particles in the variables around the range 2-20 micron had very strong negative correlations (the strongest of any of all the variables measured), much stronger than the percentage passing 45 micron.

Figure 1 shows an example of part of the plot for 50 cycle salt scaling loss in the 30A concrete. Table 11 lists the variables from the grading curve data (and their correlation coefficient) that were retained for the model building phase of the analysis.

3.2 Data Plotting

A graphical display of data can provide insight on the relationship between variables and can detect any 'abnormality' in the data.

Two-dimensional scatter plots with influence functions are often used to reveal the undue influence of data point(s) on the observed correlation. In such a plot, data points are represented by numbers ranging from 0 to 9. A '0' means the absolute value of the influence of that point on the calculation of the correlation coefficient is less than 10% and a '9' indicates its absolute influence is greater than or equal to 90%. Ideally, the graph should

consist of all '0's. For numbers greater than 2, the data point(s) may have undue influence on the observed correlation.

The results of the scatter plots can also show if there are any obvious misfits, such as outliers due to test errors, in the test data.

In some instances, the scatter plots did reveal that some data points used in this study had undue influence on the observed correlations. Figure 2 shows a typical influence plot of relative density of cement (B1) and 28 day strength of 30A concrete. As shown in the figure 2a, the correlation coefficient was 0.66. However, data point '3' (case 18 of B1) had undue influence on the observed correlation. When this point was removed, the correlation coefficient was reduced to 0.29 (figure 2b). This suggests that the correlation values in the tables may be sensitive to slight changes in the data. This is caused in large part by the small sample size used in the experiment. For the purposes of this analysis, we had no criterion for rejecting outliers so all the data points were retained.

4. ENGINEERING EVALUATION OF THE CORRELATION ANALYSIS

Before proceeding to the development of the models it was decided to review the results of the correlation analysis in terms of their engineering significance. This exercise was not intended to reject any variables from further analysis but rather to see if the conclusions to date were reasonable in terms of conventional theories about concrete behavior. The factors of concern are given in the Appendix which indicates that there is a reasonable engineering explanation for the variables identified as significant in the statistical analysis.

5. REGRESSION ANALYSIS

The most suitable technique for developing a causal equation, to predict the value of a dependent variable, is regression analysis. These equations are called 'causal ' because each of the variables in the equation is supposed to have a logical as well as statistical relationship with the dependent variable. The SYSTAT program contains a powerful set of routines called Multiple General Linear Hypothesis that can calculate several types of regression equations and apply many tests to check their statistical significance. The logical input must, however, come from the analyst.

One particular option in the SYSTAT package is stepwise regression. With this method the program reviews all the possible independent variables and introduces them into the equation one at a time in an attempt to maximize the coefficient of multiple regression. This technique is very useful in reviewing candidate variables but the resulting equations must be examined with care.

Because the correlation analysis had identified several unexpected variables as probable contributing factors, in both the compressive strength and salt scaling loss of the concretes, it was decided to have a dual approach in this phase of the analysis. In one case, an attempt was made to identify the best equation from among all the available variables. In the second, it was decided to restrict the search to only those identified variables that were already known from previous research to have an effect on either of the two dependent variables.

This approach was applied to the 28 day compressive strength and the 50 cycle salt scaling loss for each type of concrete.

Table 12 shows the final equations that were derived for the 28 day compressive strength for each concrete type (along with the most relevant statistics). In each instance the first equation was derived from all the available variables and the second from conventional variables.

Table 13 shows the equations derived for 50 cycle salt scaling loss for each concrete type.

An explanation of the details of the output is as follows:

1. SQUARED MULTIPLE R (R^2) is a measure of the success of the regression equation in explaining the variation in the data. The value is between 0 and + 1, the larger the value the better the equation. Care must be taken not to overload the equation with variables just to improve the value of this statistic.

2. STANDARD ERROR OF THE ESTIMATE is an estimate of the variation about the regression. The smaller the value the more precise will be the predictions.

3. VARIABLE lists the variables in the estimated regression equation.

4. COEFFICIENT is the calculated value of the coefficient for each variable in the equation.

5. STD ERROR is the error associated with the coefficients. Typically it would be expected that with 95% confidence the coefficient would lie within the range of the calculated value ± 2 standard errors.

6. *t* is the Student's *t* statistic for each coefficient. It is a test to see if the value of the coefficient is different to zero. Ideally the value of *t* should be larger than ± 2 for a sample of this size.

7. ANALYSIS OF VARIANCE is a test of the overall significance of the regression. The larger the value of the F-RATIO the better.

Reviewing these equations reveals the following observations:

Strength

20A concrete: A good equation was obtained using all the available variables. The multiple R is large; all of the coefficients are significant. A much poorer equation resulted from the restricted set of variables.

20B concrete: Both sets of variables gave good equations, since the variables selected for inclusion were similar in both cases.

30A concrete: Again both equations contained similar variables and were equally good. Note the small value of *t* for the constant in the second equation. This occurs in several of the examples, it is related to the inclusion of a variable in the equation that has a large mean value but a small standard deviation. To the regression equation this variable looks like a constant even though it is highly correlated to the dependent variable.

30B concrete: Both equations contained the same variables and were good.

Salt scaling

20A concrete: The overall quality of the equations was getting worse. In particular the *t* values of the coefficients were approaching 2.0 indicating low significance. The equation derived from all of the variables was marginally better than the other.

20B concrete: Both equations were identical having a very low value for R^2. The equation would be of little practical use.

30A concrete: Again the two equations were identical. The R^2 value was reasonably large. This, combined with the fact that all the coefficients were significant means that the equation has some potential.

30B concrete: Once more similar variables combined to give the best equation. The R^2 values are large, but the *t* value of the constant term is very small. This again is probably due to the inclusion of a variable, with a small percentage variability, which is highly correlated to the dependent variable.

In order to give an overall impression of the effectiveness of the equations, Figure 3 shows plots of the predicted values of each dependent variable along with the corresponding measured values.

6. DISCRIMINANT ANALYSIS

The statistical technique called discriminant analysis was developed many years ago for use in the biological sciences. Although it is used frequently in other branches of science, its use is not common in engineering.

This technique allows the researcher to study the differences between two or more groups of objects with respect to several discriminating variables simultaneously. Also, the technique provides a means to classify any case into the group which it most closely resembles.

Essentially the method works as follows. An equation is formed from a linear combination of independent variables. This equation (the discriminant function) attempts to maximize the difference between the groups. For ease of interpretation, the coefficients of the equation are 'standardized' to make the discriminant function normal with a mean value of zero and a range of about $\pm$ 3. In this way it is possible to make probability statements about the likelihood that a particular case belongs to a specified group.

To develop the equation it is first necessary to categorize the data into mutually exclusive groups. In this study two criteria were used, the 28-day compressive strength should exceed 37 MPa and the 50-cycle salt scaling loss should be less than 800 g/m^2. A concrete was classified as 'good' if it satisfied any one or both of these criteria. A concrete was classified as 'poor' only if it failed to meet both criteria.

Using this criteria, all the cases in the 30A type concretes were 'good'. The type 30B concretes had 4 'poor' and 13 'good' cases. Therefore, the 30B data were used as input to the Multiple General Linear Hypothesis module of the SYSTAT program.

Table 14 shows the output from the final trial in the development of the equation. The interpretation of the output is:

1. The required equation is obtained from the DEPENDENT VARIABLE CANONICAL COEFFICIENTS table:

$$f = 0.53\,(C18) - 0.76\,(D12) + 1.10\,(D14) + 0.21\,(D16) + 1.46\,(D18) - 0.57\,(F413)$$

where C18 is % cement between 2-20 micron, D12 is alkali content of cement, D14 is silica dioxide, D16 is ferric oxide, D18 is free calcium oxide, and F413 is effective water-cement ratio.

Note: Because f is 'standardized', the value of the variables that are input to this equation must also be in standardized form. A standardized variable has a mean value of zero and a standard deviation of one. Table 15 shows an example of converting a variable to the 'standardized' form.

2. The importance of each variable in the equation is given by the CANONICAL LOADINGS table. As with correlation coefficients, a value close to $\pm$ 1 indicates a strong similarity between the variable and the discriminant function. In the equation, a single variable does not dominate, with all the variables having similar loadings. This indicates a useful equation. Variable B7 (soundness) had more effect than D18, but was excluded from the final equation because its value was measured for only 16 of the cases.

3. The utility of the discriminant function is given by the CANONICAL CORRELATION COEFFICIENT, in this example equal to 0.91. The value is always positive and lies between 0 and +1, the larger the value the better the function.

4. Because the data used in this analysis is a single sample, it is possible that the properties of the sample are not representative of the population. We need to test the probability that the sampling process could produce cases which show the computed discrimination between groups when in fact there are no group differences in the population. This is done by a statistic called WILKS' LAMBDA. Again the value is in the range 0 to +1 but a value close to 0 indicates high discrimination. Wilks' Lambda for this application is 0.17, indicating a good discriminant function.

Table 16 shows the actual prediction for the 30B concretes. This is interpreted as follows:

1. FACTOR is the computed value of the discriminant function for each case. A negative value indicates that the case belongs in 'poor' group.

2. DISTANCE is a measure indicating how close the particular case is to each of the group centroids. A smaller number means that the case most likely belongs to that group.

3. PROB is the calculated probability that the particular case belongs to each of the identified groups.

4. GROUP is the assigned group.

5. PREDICT is the group predicted by the model.

From the result in the tables, it can be seen that the technique works well, assigning all of the concretes to their correct groups.

Discriminant analysis has two other characteristics that are useful. The first is that the maximum number of variables allowed in the equation is two less than the number of cases in the sample. Hence it is possible to derive a discriminant function that is as sensitive as necessary for the purpose of the analysis.

The second is that it is possible to adjust the probability of a case being assigned to a group. The usefulness of this property is illustrated as follows.

For this study it has been assumed that each group ('good' or 'poor' concrete) is treated equally. That is, if the probability of a case belonging to a group is just greater than 0.50 then the case is assigned to that group and vice versa. This assumes that there is no 'cost' incurred with a misclassification. In practice, there may be a large 'cost' associated with classifying a 'poor' concrete as 'good'. We might therefore like to minimize the chance of a misclassification, i.e. we would prefer to classify marginal concretes as 'poor'. In this situation we would want the evidence to be very strong before assigning a case to the 'good' group. This can be done by increasing the threshold level of the probability of acceptance for the 'good' group to 0.60, for example.

7. CONCLUSIONS AND RECOMMENDATIONS

The intent of the experiment that produced the data was necessary and timely. The results of the analysis are very promising but should not be used without verification. A major reason for this lies in the design experiment itself.

Linear causal modelling of a characteristic of a material is an attempt to devise an equation that will explain the variation of the measured value of that characteristic across many samples of the material. It is assumed that the values of the independent variables are representative of the material and error free.

Concrete is an heterogeneous material. We would therefore expect a variation in the results of an experiment, if it were repeated on several samples from the same batch of concrete. In this experiment all the important properties of concrete were measured very precisely. However, each property was only measured once. Hence, we have no knowledge about the representativeness of the measurements. We do not know if the measured values are typical or unusual. Thus, much of the inherent variability in the MTO data was not amenable to analysis.

This deficiency is illustrated in the measurement of salt scaling. For each case, two samples were produced and tested. The two results for the cases of 30A concrete differed by as much as 950 gm/m^2 in one case and typically by 300 gm/m^2. A similar spread was apparent for the other concrete types.

The experiment had another limitation, since only eighteen sources of cement were used. With so few cases it was not possible to include more than three or four variables in the regression models that were developed. In addition it was not possible to verify the accuracy of the models since all of the available data had to be used to estimate the parameters of the models. In essence there were too many variables and too few cases.

In spite of these comments the analysis has proven beneficial in a number of ways. This is perhaps the first time that a broad range of properties has been measured simultaneously for carefully prepared concrete samples. The results obtained indicate that some variables that have not previously been considered related to compressive strength and durabilty may in fact be relevant. With the experience gained from this first generation experiment it will be possible to devise another experiment that will focus on fewer properties but with more cases.

The experiment should have as many cases as possible. Theoretically, it is not possible to undertake a regression analysis if there are more variables than cases. These cases should then be divided into two sets, one set to generate the equations and the other to verify

them. The two sets do not need to be the same size, a two-third/one-third split or a 75/25% split would be satisfactory. The important consideration is to divide the groups randomly.

From the experience gained in this study, many of the variables that were measured were unimportant. Therefore the next experiment should concentrate on fewer variables, but each variable must be measured several times. There should be at least 4 repetitions of the measurement of each variable. Clearly time and cost are factors in deciding how many repetitions to make. However, it is essential to have some indication of the inherent variability of the data.

The discriminant analysis looks very promising. Given the limitations of the data, the method performed well. With more cases available it should be possible to test whether the discriminant function can forecast as well as reproduce classifications. If the method does perform well it could provide an excellent acceptance criteria for concrete.

Table 1. Results of physical tests on type 10 cements

Item			Variable
Relative density		MTO **	B1
		SLC **	B2 *
		CCL **	B3 *
Fineness	pass 45 micron	MTO	B4
	pass 45 micron	CCL	B5 *
	air permeability		B6
Soundness			B7
Set time			B8
False set			B9
Air content			B10
Compressive strength		3 day	B11
		7 day	B12
		28 day	B13

* Variables not included in statistical analysis
** MTO (Ministry of Transportation):
Le-Chatelier flask method
SLC (St. Lawrence Cement Co.): Air pycnometer method
CCL (Canada Cement Lafarge Co.): Air pycnometer method

Table 2. Particle size distribution of type 10 cements

Item	Variable
% passing 100 micron	C1
70	C2
50	C3
40	C4
30	C5
25	C6
20	C7
15	C8
10	C9
8	C10
6	C11
4	C12
2	C13
% between 2-30 micron	C14
2-50	C15
2-40	C16
2-25	C17
2-20	C18
2-15	C19
2-10	C20
10-50	C21
4-10	C22
6-10	C23
8-10	C24
4-15	C25
6-15	C26
8-15	C27
4-20	C28
6-20	C29
8-20	C30
2-4	C31
2-6	C32
2-8	C33

Table 2 (cont'd). Particle size distribution of type 10 cements

Item	Variable
% between 10-15 micron	C34
10-20	C35
10-25	C36
10-30	C37
10-40	C38
10-70	C39
15-20	C40
15-25	C41
15-30	C42
15-40	C43
15-50	C44
15-70	C45
6-8	C46
6-25	C47
6-30	C48
6-40	C49
6-50	C50
4-6	C51
4-8	C52
4-25	C53
4-30	C54
4-40	C55
Total specific area	SA15

Table 3. Results of chemical tests on type 10 cements

Item		Variable
Loss on ignition	MTO **	D1
	ST. MARYS(550) **	D2 *
	ST. MARYS(1000)**	D3 *
Insoluble residue		D4
Tricalcium aluminate		D5
Sulphur trioxide		D6
Magnesium oxide		D7
Sodium oxide	MTO	D8
	CCL	D9 *
Potassium oxide	MTO	D10
	CCL	D11*
Alkali content	MTO	D12
	CCL	D13*
Silicon dioxide		D14
Aluminium oxide		D15
Ferric oxide		D16
Calcium oxide		D17
Free calcium oxide		D18
Carbonate addition		D19
Tricalcium silicate		D20
Dicalcium silicate		D21
Tetracalcium aluminoferrite		D22

* Variables not included in statistical analysis
** MTO: Loss at 1050°C
ST. MARYS(550): Loss at 550°C
ST. MARYS(1000): Loss at 1000°C

Table 4. Concrete mix proportions and test results

Item	Variable			
	20A	30A	20B	30B
Fine aggregate	F11	F21	F31	F41
Coarse aggregate	F12	F22	F32	F42
Cement	F13	F23	F33	F43
Water (total)	F14	F24	F34	F44
Water reducing agent WRDA	F15	F25	F35	F45
Air entraining agent DAREX AEA	F16	F26	F36	F46
Slump	F17	F27	F37	F47
Air content	F18	F28	F38	F48
Density	F19	F29	F39	F49
Yield	F110	F210	F310	F410
Cement content	F111	F211	F311	F411
Effective water-cement ratio	F112	F212	F312	F412
Effective water-cement ratio*	F113	F213	F313	F413

* Based on cement passing 45 micron sieve

Table 5. Concrete compressive strength

Item		Variable			
		20A	30A	20B	30B
Compressive strength	3 day	G11	G15	G21	G25
	7 day	G12	G16	G22	G26
	28 day	G13	G17	G23	G27
	91 day	G14	G18	G24	G28

Table 6. Concrete salt scaling loss

Item		Variable			
		20A	30A	20B	30B
Cummulative mass loss	5 cycle	I11	I16	I21	I26
	10 cycle	I12	I17	I22	I27
	15 cycle	I13	I18	I23	I28
	25 cycle	I14	I19	I24	I29
	50 cycle	I15	I110	I25	I210

Table 7. Concrete air void system parameters

Item			Variable			
			20A	30A	20B	30B
Air entraining agent DAREX AEA		*	J11	J21	J31	J 1
Air content (fresh concrete)		*	J12	J22	J32	J42
Linear traverse:						
Air void content	total		J13	J23	J33	J43
	<1mm	*	J14	J24	J34	J44
	<.5mm	*	J15	J25	J35	J45
Voids per 25mm	total		J16	J26	J36	J46
	<1mm	*	J17	J27	J37	J47
	<.5mm	*	J18	J28	J38	J48
Average chord length	total		J19	J29	J39	J49
	<1mm	*	J110	J210	J310	J410
	<.5mm	*	J111	J211	J311	J411
Paste-air ratio	total		J112	J212	J312	J412
	<1mm	*	J113	J213	J313	J413
	<.5mm	*	J114	J214	J314	J414
Specific surface	total		J115	J215	J315	J415
	<1mm	*	J116	J216	J316	J416
	<.5mm	*	J117	J217	J317	J417
Spacing factor	total		J118	J218	J318	J418
	<1mm	*	J119	J219	J319	J419
	<.5mm	*	J120	J220	J320	J420
% air x 1.5		*	J121	J221	J321	J421
50 cycle scaling loss		*	J122	J222	J322	J422

* Variables not included in statistical analysis

Table 8a. Variables in this study potentially important to 28 day strength of 20A and 20B concretes

20A Concrete

Independent Variable		Coefficient
B1	Relative density, cement	0.456
B7	Soundness, cement	-0.664
B8	Set time, cement	0.463
C4	% passing 40 micron sieve, cement	0.404
D6	Sulphur trioxide, cement	-0.427
D10	Potassium oxide, cement	-0.467
D12	Alkali content, cement	-0.570
D14	Silicon dioxide, cement	0.525
D18	Free calcium oxide, cement	-0.480
D19	Carbonate addition, cement	-0.400
J16	Voids per 25mm (total), Concrete	0.448
J19	Chord length (total), concrete	-0.472
J115	Void specific surface (total), concrete	0.441
J118	Spacing factor (total),concrete	-0.519

20B Concrete

Independent Variable		Coefficient
B1	Relative density, cement	0.592
B7	Soundness, cement	-0.590
B8	Set time, cement	0.546
B11	3 day strength, cement	-0.488
D5	Tricalcium aluminate, cement	-0.453
D6	Sulphur trioxide, cement	-0.534
D10	Potassium oxide, cement	-0.713
D12	Alkali content, cement	-0.850
D14	Silicon dioxide, cement	0.599
D16	Ferric oxide, cement	0.579
D18	Free calcium oxide, cement	-0.684
D22	Tetracalcium aluminoferrite, cement	0.579
F34	Water (total), concrete	-0.409
F37	Slump, concrete	-0.552
F38	Air content, concrete	-0.404
F39	Relative density, concrete	0.644
F310	Yield, concrete	-0.762
F311	Cement content, concrete	0.774
F312	Effective water-cement ratio, concrete	-0.425
F313	Effective water-cement ratio*, concrete	-0.457

* Based on cement passing 45 micron sieve

Table 8b. Variables in this study potentially important to 28 day strength of 30A and 30B concretes

30A Concrete

Independent variable		Coefficient
B1	Relative density, cement	0.568
B4	Fineness (pass 45 micron sieve), cement	0.445
B7	Soundness, cement	-0.475
B8	Set time, cement	0.548
B9	False set, cement	0.451
B13	28 day strength, cement	0.598
C3	% passing 50 micron sieve, cement	0.547
D1	Loss on ignition, cement	-0.407
D5	Tricalcium aluminate, cement	-0.457
D10	Potassium oxide, cement	-0.601
D12	Alkali content, cement	-0.745
D16	Ferric oxide, cement	0.683
D19	Carbonate addition, cement	-0.541
D22	Tetracalcium aluminoferrite, cement	0.683
F29	Relative density, concrete	0.457
F210	Yield, concrete	-0.432
F211	Cement content, concrete	0.453

30B Concrete

Independent Variable		Coefficient
B1	Relative density, cement	0.439
B7	Soundness, cement	-0.577
B8	Set time, cement	0.430
B11	3 day strength, cement	-0.433
D5	Tricalcium aluminate, cement	-0.490
D6	Sulphur trioxide, cement	-0.619
D10	Potassium oxide, cement	-0.621
D12	Alkali content, cement	-0.788
D14	Silicon dioxide, cement	0.622
D15	Aluminium oxide, cement	-0.461
D16	Ferric oxide, cement	0.435
D17	Calcium oxide, cement	0.492
D18	Free calcium oxide, cement	-0.510
D19	Carbonate addition, cement	-0.426
D22	Tetracalcium aluminoferrite, cement	0.435
F48	Air content, concrete	-0.530
F49	Relative density, concrete	0.558
F410	Yield, concrete	-0.617
F411	Cement content, concrete	0.621
F413	Effective water-cement ratio*, concrete	-0.406
J43	Air void content (total), concrete	-0.533
J412	Paste-air ratio (total), concrete	0.480

* Based on cement passing 45 micron sieve

Table 8c. Variables in this study potentially important to 50 cycle salt scaling loss of 20A and 20B concretes

20A Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	-0.664
B8	Set time, cement	-0.421
C18	% between 2-20 micron, cement	-0.786
D4	Insoluble residue, cement	0.485
D5	Tricalcium aluminate, cement	0.674
D15	Aluminium oxide, cement	0.681
D16	Ferric oxide, cement	-0.492
D20	Tricalcium silicate, cement	-0.406
D22	Tetracalcium aluminoferrite, cement	-0.492
F113	Effective water-cement ratio*, concrete	0.684
G13	28 day strength, concrete	-0.519
G14	91 day strength, concrete	-0.482
J13	Air void content (total), concrete	-0.586
J16	Voids per 25mm (total), concrete	-0.490
J112	Paste-air ratio (total), concrete	0.606

20B Concrete

Independent Variable		Coefficient
B8	Set time, cement	-0.452
C28	% between 4-20 micron, cement	-0.527
F36	DAREX AEA dosage	0.461
F38	Air content, concrete	-0.463
G21	3 day strength, concrete	-0.431

* Based on cement passing 45 micron sieve

Table 8d. Variables in this study potentially important to 50 cycle salt scaling loss of 30A and 30B concretes

30A Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	-0.610
C18	% between 2-20 micron, cement	-0.752
D4	Insoluble residue, cement	0.582
D5	Tricalcium aluminate, cement	0.647
D10	Potassium oxide, cement	0.481
D15	Aluminium oxide, cement	0.663
D16	Ferric oxide, cement	-0.443
D20	Tricalcium silicate, cement	-0.456
D22	Tetracalcium aluminoferrite, cement	-0.443
F24	Water (total), concrete	0.507
F210	Yield, concrete	0.430
F211	Cement content, concrete	-0.403
F212	Effective water-cement ratio, concrete	0.431
F213	Effective water-cement ratio*, concrete	0.671
G16	7 day strength, concrete	-0.597
G17	28 day strength, concrete	-0.442
G18	91 day strength, concrete	-0.629
J29	Average chord length (total), concrete	0.432
J218	Spacing factor (total), concrete	0.401
SA15	Specific surface area, cement	0.434

30B Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	-0.619
B8	Set time, cement	-0.458
C18	% between 2-20 micron, cement	-0.718
D4	Insoluble residue, cement	0.495
D5	Tricalcium aluminate, cement	0.614
D10	Potassium oxide, cement	0.498
D12	Alkali content, cement	0.476
D15	Aluminium oxide, cement	0.568
D16	Ferric oxide, cement	-0.574
D22	Tetracalcium aluminoferrite, cement	-0.574
F48	Air content, concrete	-0.457
F413	Effective water-cement ratio*, concrete	0.731

* Based on cement passing 45 micron sieve

Table 9a. Variables in this study possibly important to 28 day strength of 20A and 20B concretes

20A Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	0.306
B9	False set, cement	0.242
B10	Air content, cement	0.265
B11	3 day strength, cement	-0.279
B13	28 day strength, cement	0.322
D1	Loss on ignition, cement	-0.337
D5	Tricalcium aluminate, cement	-0.391
D15	Aluminium oxide, cement	-0.368
D16	Ferric oxide, cement	0.365
D17	Calcium oxide, cement	0.277
D21	Dicalcium silicate, cement	0.231
D22	Tetracalcium aluminoferrite, cement	0.365
F16	DAREX AEA dosage	0.275
SA15	Specific surface area, cement	-0.207

20B Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	0.266
B9	False set, cement	0.261
B13	28 day strength, cement	0.352
D1	Loss on ignition, cement	-0.392
D4	Insoluble residue, cement	-0.214
D15	Aluminium oxide, cement	-0.381
D17	Calcium oxide, cement	0.390
D19	Carbonate addition, cement	-0.326
F36	DAREX AEA dosage	0.254

Table 9b. Variables in this study possibly important to 28 day strength of 30A and 30B concretes

30A Concrete

Independent Variable		Coefficient
B11	3 day strength, cement	-0.390
B12	7 day strength, cement	0.233
D4	Insoluble residue, cement	-0.372
D6	Sulphur trioxide, cement	-0.381
D7	Magnesium oxide, cement	0.209
D14	Silicon dioxide, cement	0.389
D15	Aluminium oxide, cement	-0.344
D17	Calcium oxide, cement	0.222
D18	Free calcium oxide, cement	-0.311
F28	Air content, concrete	-0.360
F213	Effective water-cement ratio*, concrete	-0.341
J23	Air void content (total), concrete	-0.280
J212	Paste-air ratio (total), concrete	0.266
SA15	Specific surface area, cement	-0.343

30B Concrete

Independent Variable		Coefficient
B4	Fineness (pass 45 micron sieve), cement	0.251
B9	False set, cement	0.245
B13	28 day strength, cement	0.268
D1	Loss on ignition, cement	-0.388
D4	Insoluble residue, cement	-0.357
D7	Magnesium oxide (MgO), cement	0.247
D21	Dicalcium silicate, cement	0.207
F44	Water (total), concrete	-0.290
F46	DAREX AEA dosage	0.339
F47	Slump, concrete	-0.265
F412	Effective water-cement ratio, concrete	-0.316
J46	Voids per 25mm (total), concrete	-0.399

* Based on cement passing 45 micron sieve

Table 9c. Variables in this study possibly important to 50 cycle salt scaling loss of 20A and 20B concretes

20A Concrete

Independent Variable		Coefficient
B1	Relative density, cement	-0.237
B6	Fineness (air permeability), cement	-0.206
B7	Soundness, cement	0.368
B13	28 day strength, cement	-0.363
D7	Magnesium oxide, cement	-0.326
D8	Sodium oxide, cement	-0.222
D10	Potassium oxide, cement	0.398
D12	Alkali content, cement	0.326
D14	Silicon dioxide, cement	-0.297
D17	Calcium oxide, cement	-0.327
D19	Carbonate addition, cement	0.275
D21	Dicalcium silicate, cement	0.202
F14	Water (total), concrete	0.327
F17	Slump, concrete	-0.329
F110	Yield, concrete	0.334
F111	Cement content, concrete	-0.339
F112	Effective water-cement ratio, concrete	0.325
G12	7 day strength, concrete	-0.228
J118	Spacing factor (total), concrete	0.301
SA15	Specific surface area, cement	0.253

20B Concrete

Independent Variable		Coefficient
B6	Fineness (air permeability), cement	0.349
D6	Sulphur trioxide, cement	-0.393
D8	Sodium oxide, cement	0.311
D10	Potassium oxide, cement	-0.287
D14	Silicon dioxide, cement	0.273
D19	Carbonate addition, cement	0.289
D21	Dicalcium silicate, cement	0.243
F39	Relative density, concrete	0.286
G22	7 day strength, concrete	-0.315
J33	Air void content (total), concrete	-0.210
J312	Paste-air ratio (total), concrete	0.210
SA15	Specific surface area, cement	0.346

Table 9d. Variables in this study possibly important to 50 cycle salt scaling loss of 30A and 30B concretes

30A Concrete

Independent Variable		Coefficient
B1	Relative density, cement	-0.232
B7	Soundness, cement	0.206
B9	False set, cement	-0.247
B13	28 day strength, cement	-0.337
D7	Magnesium oxide, cement	-0.387
D8	Sodium oxide, cement	-0.263
D12	Alkali content, cement	0.393
D14	Silicon dioxide, cement	-0.228
D17	Calcium oxide, cement	-0.267
D21	Dicalcium silicate, cement	0.266
F27	Slump, concrete	0.278
F29	Relative density, concrete	-0.298
J23	Air void content (total), concrete	0.280
J26	Voids per 25mm (total), concrete	0.265
J215	Void specific surface (total), concrete	-0.292

30B Concrete

Independent Variable		Coefficient
B1	Relative density, cement	-0.291
B7	Soundness, cement	0.206
B10	Air content, cement	0.350
B13	28 day strength, cement	-0.337
D7	Magnesium oxide, cement	-0.372
D20	Tricalcium silicate, cement	-0.206
F44	Water (total), concrete	0.362
F46	DAREX AEA dosage	-0.228
F47	Slump, concrete	0.262
G26	7 day strength, concrete	-0.276
G27	28 day strength, concrete	-0.285
G28	91 day strength, concrete	-0.398
J46	Voids per 25mm (total), concrete	-0.286
J49	Average chord length (total), concrete	0.259
J415	Void specific surface (total), concrete	-0.227
J418	Spacing factor (total), concrete	0.360
SA15	Specific surface area, cement	0.398

Table 10a. Variables in this study not related to 28 day strength of 20A and 20B concretes

20A Concrete

B6	Fineness (air permeability), cement
B12	7 day strength, cement
D4	Insoluble residue, cement
D7	Magnesium oxide, cement
D8	Sodium oxide, cement
D20	Tricalcium silicate, cement
F14	Water (total), concrete
F17	Slump, concrete
F18	Air content, concrete
F19	Relative density, concrete
F110	Yield, concrete
F111	Cement content, concrete
F112	Effective water-cement ratio, concrete
F113	Effective water-cement ratio*, concrete
J13	Air void content (total), concrete
J112	Paste-air ratio (total), concrete

20B Concrete

B6	Fineness (air permeability)
B10	Air content, cement
B12	7 day strength, cement
D7	Magnesium oxide, cement
D8	Sodium oxide, cement
D20	Tricalcium silicate, cement
D21	Dicalcium silicate, cement
J33	Air void content, concrete
J36	Voids per 25mm (total), concrete
J39	Average chord length (total), concrete
J312	Paste-air ratio (total), concrete
J315	Void specific surface (total), concrete
J318	Spacing factor (total), concrete
SA15	Specific surface area, cement

* Based on cement passing 45 micron sieve

Table 10b. Variables in this study not related to 28 day strength of 30A and 30B concretes

30A Concrete

B6	Fineness (air permeability), cement
B10	Air content, cement
D8	Sodium oxide, cement
D20	Tricalcium silicate, cement
D21	Dicalcium silicate, cement
F24	Water (total), concrete
F26	DAREX AEA dosage
F27	Slump, concrete
F212	Effective water-cement ratio, concrete
J26	Voids per 25mm (total), concrete
J29	Average chord length (total), concrete
J215	Void specific surface (total), concrete

30B Concrete

B6	Fineness (air permeability), cement
B10	Air content, cement
B12	7 day strength, cement
D8	Sodium oxide, cement
D20	Tricalcium silicate, cement
J49	Average chord length (total), concrete
J415	Void specific surface (total), concrete
J418	Spacing factor (total), concrete

Table 10c. Variables in this study not related to 50 cycle salt scaling loss of 20A and 20B concretes

20A Concrete

B9	False set, cement
B10	Air content, cement
B11	3 day strength, cement
B12	7 day strength, cement
D1	Loss on ignition, cement
D6	Sulphur trioxide, cement
D18	Free calcium oxide, cement
F16	DAREX AEA dosage
F18	Air content, concrete
F19	Relative density, concrete
G11	3 day strength, concrete
J19	Average chord length (total), concrete
J115	Void specific surface (total), concrete

20B Concrete

B1	Relative density, cement
B7	Soundness, cement
B9	False set, cement
B10	Air content, cement
B11	3 day strength, cement
B12	7 day strength, cement
D1	Loss on ignition, cement
D4	Insoluble residue, cement
D5	Tricalcium aluminate, cement
D7	Magnesium oxide, cement
D12	Alkali content, cement
D15	Aluminium oxide, cement
D16	Ferric oxide, cement
D17	Calcium oxide, cement
D18	Free calcium oxide, cement
D20	Tricalcium silicate, cement
D22	Tetracalcium aluminoferrite, cement
F34	Water (total), concrete
F37	Slump, concrete
F310	Yield, concrete
F311	Cement content, concrete
F312	Effective water-cement ratio, concrete
F313	Effective water-cement ratio*, concrete
G23	28 day strength, concrete
G24	91 day strength, concrete
J36	Voids per 25mm (total), concrete
J39	Average chord length (total), concrete
J315	Void specific surface (total), concrete
J318	Spacing factor (total), concrete

* Based on cement passing 45 micron sieve

Table 10d. Variables in this study not related to 50 cycles salt scaling loss of 30A and 30B concretes

30A Concrete

B6	Fineness (air permeability), cement
B8	Set time, cement
B10	Air content, cement
B11	3 day strength, cement
B12	7 day strength, cement
D1	Loss on ignition, cement
D6	Sulphur trioxide, cement
D18	Free calcium oxide, cement
D19	Carbonate addition, cement
F26	DAREX AEA dosage
F28	Air content, concrete
G15	3 day strength, concrete
J26	Voids per 25mm (total), concrete
J29	Average chord length (total), concrete
J215	Void specific surface (total), concrete
J218	Spacing factor (total), concrete

30B Concrete

B6	Fineness (air permeability), cement
B9	False set, cement
B11	3 day strength, cement
B12	7 day strength, cement
D1	Loss on ignition, cement
D6	Sulphur trioxide, cement
D8	Sodium oxide, cement
D14	Silicon dioxide, cement
D17	Calcium oxide, cement
D18	Free calcium oxide, cement
D19	Carbonate addition, cement
D21	Dicalcium silicate, cement
F49	Relative density, concrete
F410	Yield, concrete
F411	Cement content, concrete
G25	3 day strength, concrete
J43	Air void content (total), concrete
J412	Paste-air ratio (total), concrete
SA15	Specific surface area, cement

Table 11. Potentially important variables from the grading curve

Case	Variable	Coefficient
28 day strength 20A concrete	C4	0.404
28 day strength 20B concrete	none	-
28 day strength 30A concrete	C3	0.547
28 day strength 30B concrete	none	-
50 cycle salt scaling 20A concrete	C18	-0.786
50 cycle salt scaling 20B concrete	C28	-0.527
50 cycle salt scaling 30A concrete	C18	-0.752
50 cycle salt scaling 30B concrete	C18	-0.718

Table 12a. Regression analysis for 28 day strength of 20A concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.86

STANDARD ERROR OF ESTIMATE: 1.09

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		-128.49	39.38	-3.26
Soundness, cement	B7	-18.23	4.75	-3.84
Avg. chord length	J19	-43.91	10.63	-4.13
Density, cement	B1	52.69	12.59	4.19
% passing 40 micron, cement	C4	0.18	0.08	2.29

ANALYSIS OF VARIANCE F-RATIO: 17.07

CASE 2: Selected variables

SQUARED MULTIPLE R: 0.38

STANDARD ERROR OF ESTIMATE: 2.13

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		48.49	3.35	14.46
Alkali content, cement	D12	8.97	4.23	-2.12
Carbonate addition, cement	D19	-0.43	0.42	-1.03

ANALYSIS OF VARIANCE F-RATIO: 3.90

Table 12b. Regression analysis for 28 day strength of 20B concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.89

STANDARD ERROR OF ESTIMATE: 1.13

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		45.28	2.21	20.45
Alkali content, cement	D12	-15.21	2.32	-6.55
Free calcium oxide, cement	D18	-1.76	0.72	-2.45
Set time, cement	B8	0.03	0.01	3.20

ANALYSIS OF VARIANCE F-RATIO: 34.97

Case 2: Selected variables

SQUARED MULTIPLE R: 0.84

STANDARD ERROR OF ESTIMATE: 1.32

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		44.62	2.56	17.44
Alkali content, cement	D12	-17.15	2.54	-6.74
Set time, cement	B8	0.04	0.01	3.55

ANALYSIS OF VARIANCE F-RATIO: 36.48

Table 12c. Regression analysis for 28 day strength of 30A concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.78

STANDARD ERROR OF ESTIMATE: 2.09

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		-163.23	85.30	-1.91
Alkali content, cement	D12	-14.86	4.50	-3.31
% passing 50 micron, cement	C3	0.55	0.19	2.85
Density, cement	B1	55.05	25.91	2.13

ANALYSIS OF VARIANCE F-RATIO: 13.87

Case 2: Selected variables

SQUARED MULTIPLE R: 0.78

STANDARD ERROR OF ESTIMATE: 2.10

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		15.80	18.65	0.85
Alkali content, cement	D12	-16.38	4.24	-3.87
% passing 50 micron, cement	C3	0.49	0.19	2.54
Carbonate addition, cement	D19	-0.86	0.41	-2.11

ANALYSIS OF VARIANCE F-RATIO: 13.79

Table 12d. Regression analysis for 28 day strength of 30B concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.88

STANDARD ERROR OF ESTIMATE: 1.22

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		71.23	4.46	15.99
Alkali content, cement	D12	-16.12	2.36	-6.84
Air content, concrete	F48	-3.04	0.70	-4.33
Carbonate addition, cement	D19	-0.55	0.21	-2.66

ANALYSIS OF VARIANCE F-RATIO: 30.81

Case 2: Selected variables

SQUARED MULTIPLE R: 0.88

STANDARD ERROR OF ESTIMATE: 1.22

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		71.23	4.46	15.99
Alkali content, cement	D12	-16.12	2.36	-6.84
Air content, concrete	F48	-3.04	0.70	-4.33
Carbonate addition, cement	D19	-0.55	0.21	-2.66

ANALYSIS OF VARIANCE F-RATIO: 30.81

Table 13a. Regression analysis for 50 cycle salt scaling loss of 20A concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.74

STANDARD ERROR OF ESTIMATE: 215

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		1858.58	1336.15	1.39
% between 2-20 micron, cement	C18	-26.59	22.04	-1.21
Aluminum oxide, cement	D15	238.08	99.81	2.39
Air void content, concrete	J13	-195.34	112.52	-1.74

ANALYSIS OF VARIANCE F-RATIO: 11.23

Case 2: Selected variables

SQUARED MULTIPLE R: 0.66

STANDARD ERROR OF ESTIMATE: 233

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		3048.68	1202.16	2.54
% passing 2-20 micron, cement	C18	-52.06	18.31	-2.84
Tricalcium aluminate, cement	D5	52.28	31.09	1.68

ANALYSIS OF VARIANCE F-RATIO: 12.83

Table 13b. Regression analysis for 50 cycle salt scaling loss of 20B concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.28

STANDARD ERROR OF ESTIMATE: 1160

VARIABLE	COEFFICIENT	STD ERROR	t
Constant	10673.21	3773.84	2.83
% between 4-20 micron, cement C28	-203.88	84.79	-2.40

ANALYSIS OF VARIANCE F-RATIO: 5.78

Case 2: Selected variables

SQUARED MULTIPLE R: 0.28

STANDARD ERROR OF ESTIMATE: 1160

VARIABLE	COEFFICIENT	STD ERROR	t
Constant	10673.21	3773.84	2.83
% between 4-20 micron, cement C28	-203.88	84.79	-2.40

ANALYSIS OF VARIANCE F-RATIO: 5.78

Table13c. Regression analysis for 50 cycle salt scaling loss of 30A concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.68

STANDARD ERROR OF ESTIMATE: 245

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		3705.41	928.98	3.99
% between 2-20 micron, cement	C18	-66.95	15.75	-4.25
Potassium oxide, cement	D10	577.65	270.49	2.14

ANALYSIS OF VARIANCE F-RATIO: 13.71

Case 2: Selected variables

SQUARED MULTIPLE R: 0.68

STANDARD ERROR OF ESTIMATE: 245

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		3705.41	928.98	3.99
% between 2-20 micron, cement	C18	-66.95	15.75	-4.25
Potassium oxide, cement	D10	577.65	270.49	2.14

ANALYSIS OF VARIANCE F-RATIO: 13.71

Table 13d. Regression analysis for 50 cycle salt scaling loss of 30B concrete

Case 1: All variables

SQUARED MULTIPLE R: 0.80

STANDARD ERROR OF ESTIMATE: 237

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		-748.56	1235.89	-0.61
Effective w/c ratio	F413	8674.63	1866.58	4.65
Air content, concrete	F48	-492.64	135.37	-3.64
Insoluble residue, cement	D4	622.65	310.77	2.00

ANALYSIS OF VARIANCE F-RATIO: 17.08

Case 2: Selected variables

SQUARED MULTIPLE R: 0.76

STANDARD ERROR OF ESTIMATE: 256

VARIABLE		COEFFICIENT	STD ERROR	t
Constant		1646.93	2639.29	0.62
Effective w/c ratio	F413	7333.65	2861.26	2.56
Air content, concrete	F48	-452.65	148.54	-3.05
% between 2-20 micron, cement	C18	-31.83	25.20	-1.26

ANALYSIS OF VARIANCE F-RATIO: 14.04

Table 14. Equation output for 30B concrete in discriminant analysis

WILKS' LAMBDA: 0.17

CANONICAL CORRELATIONS: 0.91

DEPENDENT VARIABLE CANONICAL COEFFICIENTS
STANDARDIZED BY CONDITIONAL (WITHIN GROUPS) STANDARD DEVIATIONS

% between 2-20 micron, cement	C18	0.53
Effective water-cement ratio	F413	-0.57
Akali content, cement	D12	-0.76
Silicon dioxide, cement	D14	1.10
Ferric oxide, cement	D16	0.21
Free calcium oxide, cement	D18	1.46

CANONICAL LOADINGS (CORRELATIONS BETWEEN CONDITIONAL
DEPENDENT VARIABLES AND DEPENDENT CANONICAL FACTORS)

% between 2-20 micron, cement	C18	0.27
Effective water-cement ratio	F413	-0.40
Akali content, cement	D12	-0.34
Silicon dioxide, cement	D14	0.17
Ferric oxide, cement	D16	0.29
Free calcium oxide, cement	D18	0.09

Table 15. Standardization of variable D14

	Original Values x	Standardized Values z
	19.42	-1.69
	18.96	-2.36
	20.03	-0.80
	20.91	0.48
	20.50	-0.12
	20.27	-0.45
	21.58	1.45
	20.22	-0.52
	21.25	0.97
	20.68	0.14
	19.84	-1.08
	20.86	0.41
	21.40	1.19
	20.62	0.06
	21.01	0.62
	20.88	0.44
	20.92	0.49
	21.10	0.76
Mean (μ)	20.58	0.00
Standard Deviation (σ)	0.69	1.00
Conversion	$z = \frac{x - \mu}{\sigma}$	

Table 16. Prediction for 30B concrete in discriminant analysis

CASE	FACTOR	DISTANCE(1)	DISTANCE(2)	PROB(1)	PROB(2)	GROUP*	PREDICT*
1	-4.26	5.42	0.49	0.00	1.00	2	2
2	1.26	0.11	5.03	1.00	0.00	1	1
3	-5.81	6.97	2.05	0.00	1.00	2	2
4	-3.46	4.62	0.30	0.00	1.00	2	2
5	0.94	0.21	4.71	1.00	0.00	1	1
6	2.21	1.05	5.97	1.00	0.00	1	1
7	-1.52	2.68	2.24	0.25	0.75	2	2
8	0.80	0.36	4.57	1.00	0.00	1	1
9	1.44	0.28	5.21	1.00	0.00	1	1
10	0.52	0.64	4.28	1.00	0.00	1	1
11	1.05	0.11	4.81	1.00	0.00	1	1
12	0.26	0.90	4.02	1.00	0.00	1	1
13	1.64	0.48	5.40	1.00	0.00	1	1
14	2.01	0.86	5.78	1.00	0.00	1	1
15	1.13	0.03	4.89	1.00	0.00	1	1
16	-0.04	1.20	3.73	1.00	0.00	1	1
17	1.83	0.68	5.60	1.00	0.00	1	1

* 1 - 'good' concrete
  2 - 'poor' concrete

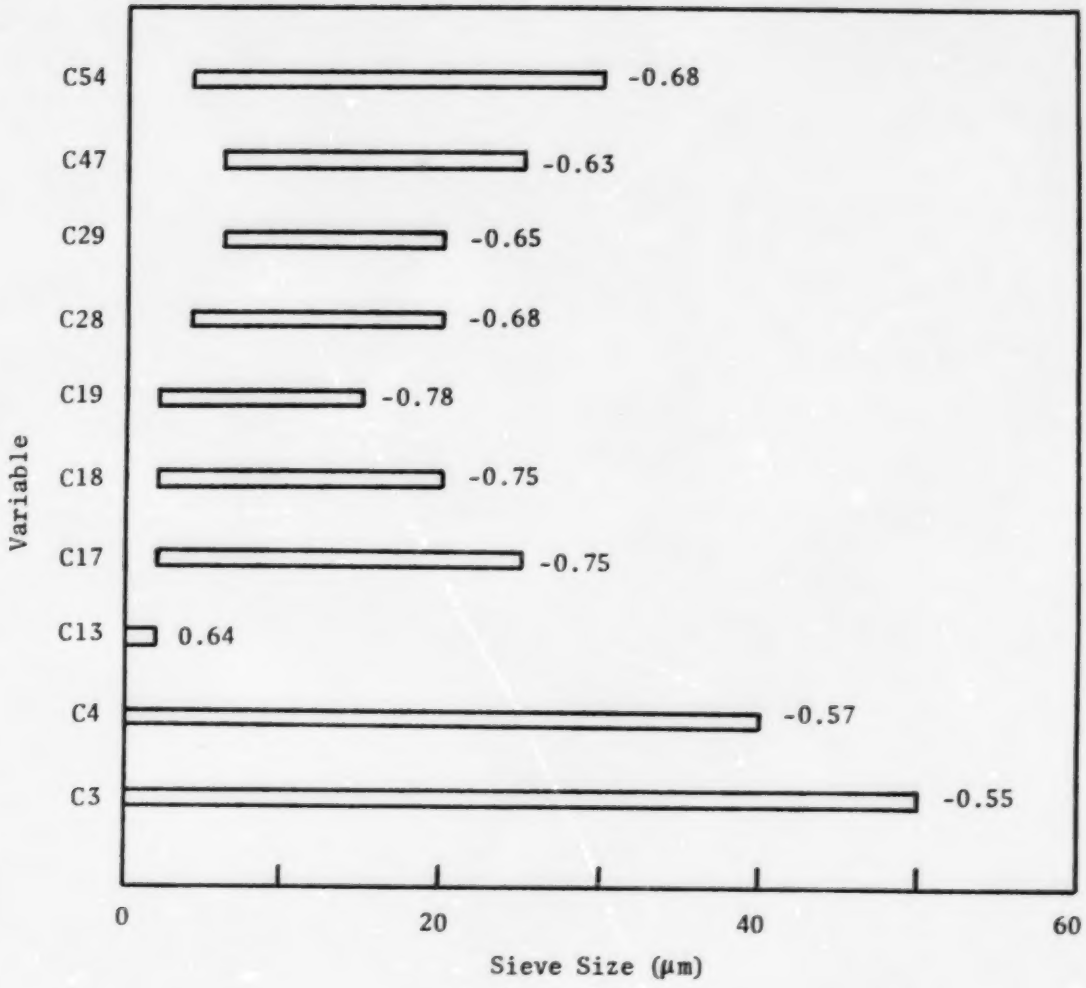


Figure 1. Correlation coefficients for 50 cycle salt scaling loss and typical variables from the grading curve: ▭ Length of line represents range of sieve sizes

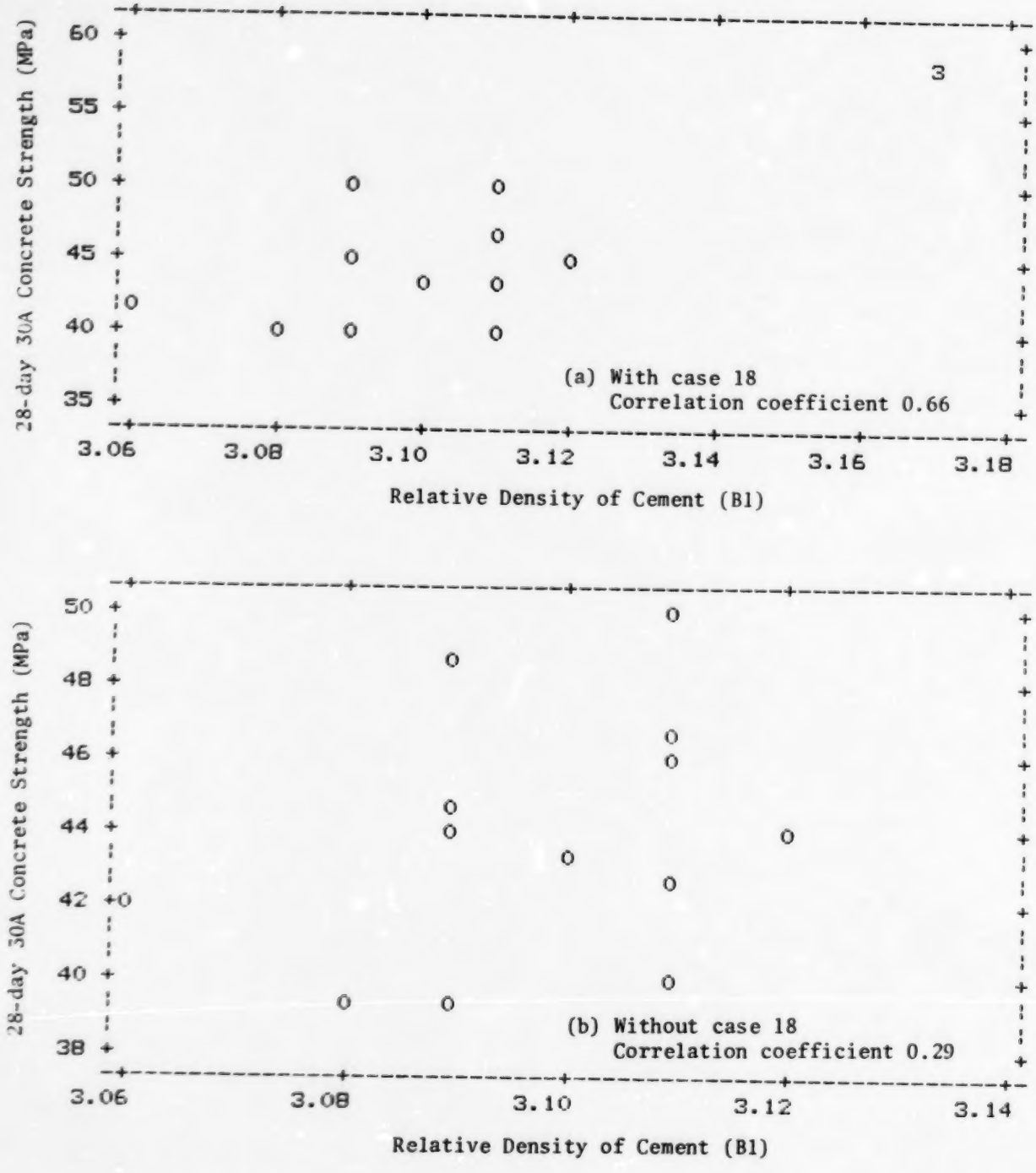
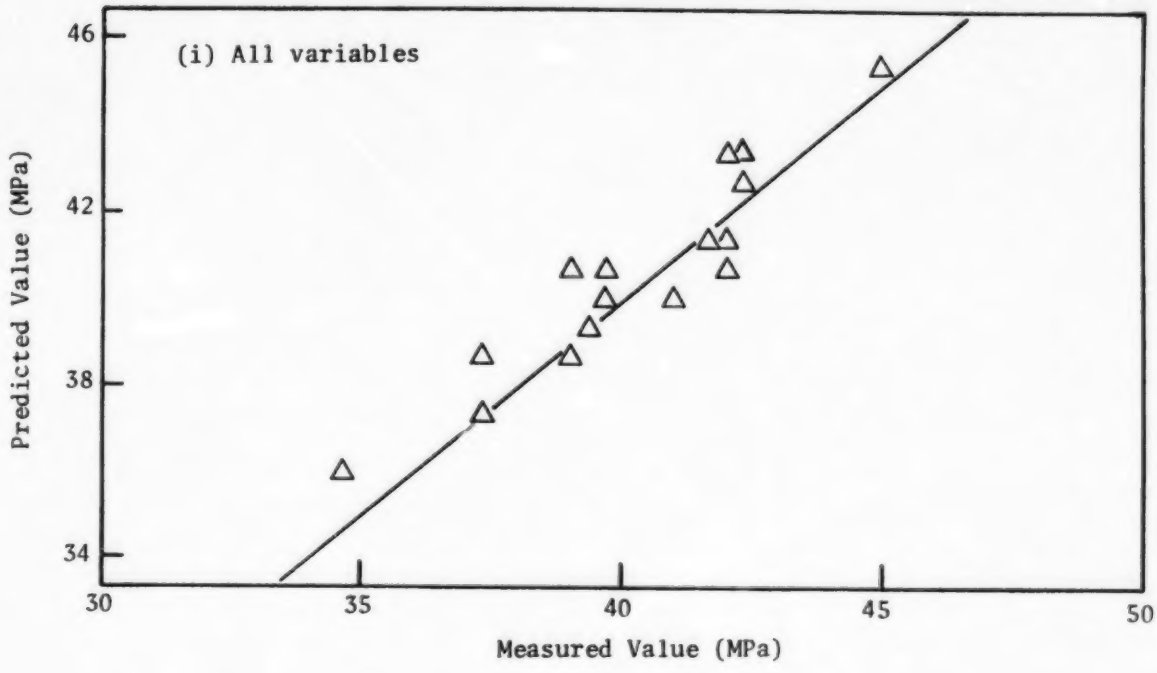


Figure 2. Influence plot of relative density of cement and 28 day strength of 30A concrete



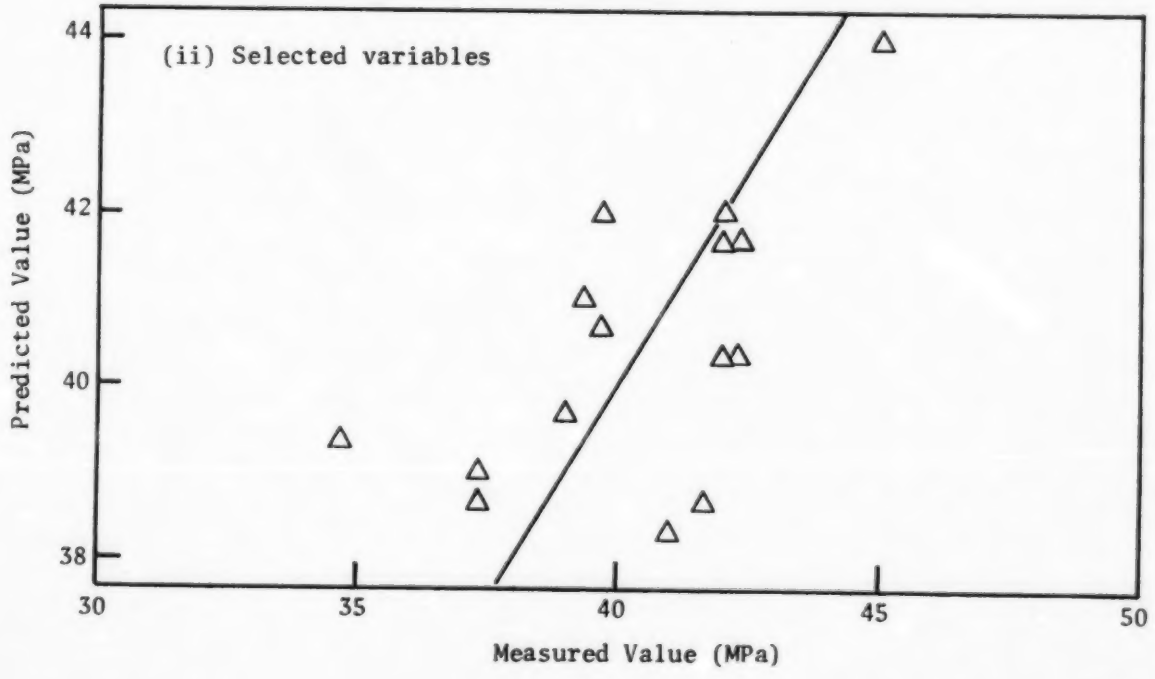
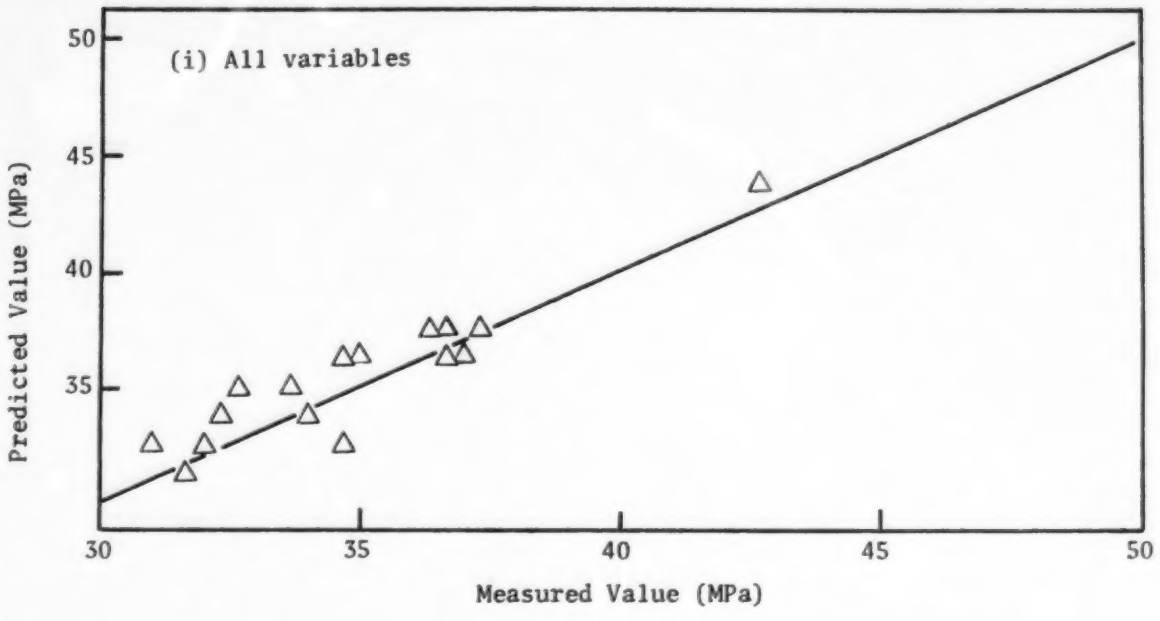


Figure 3a. Predicted and measured values of 28 day strength for 20A concrete: —— 'Ideal' line where predicted value = measured value



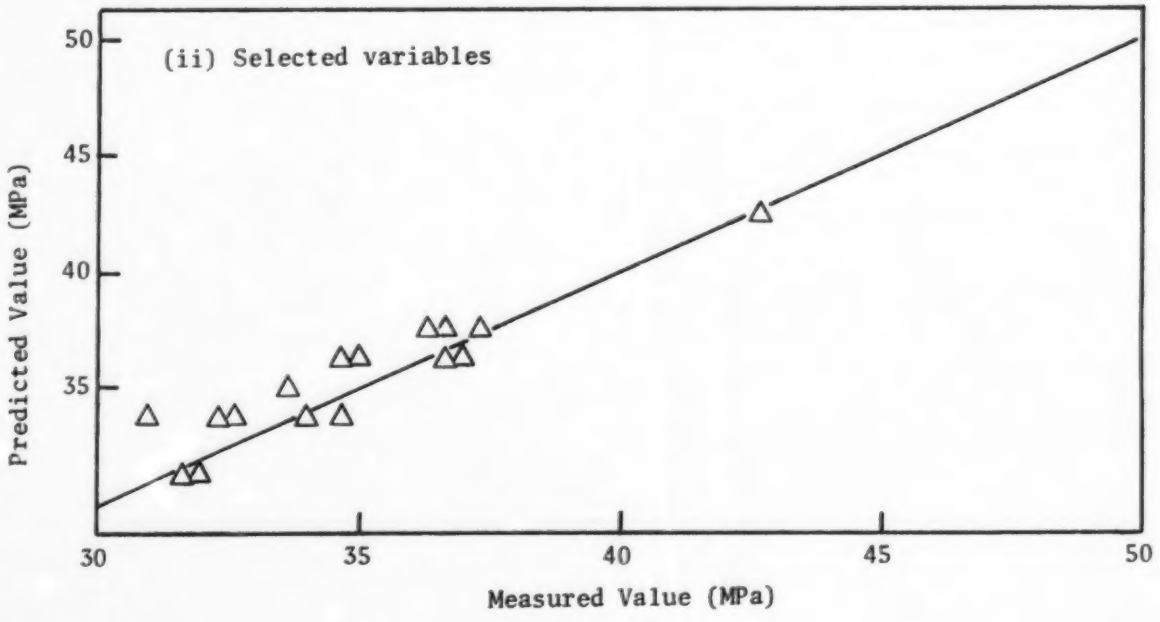
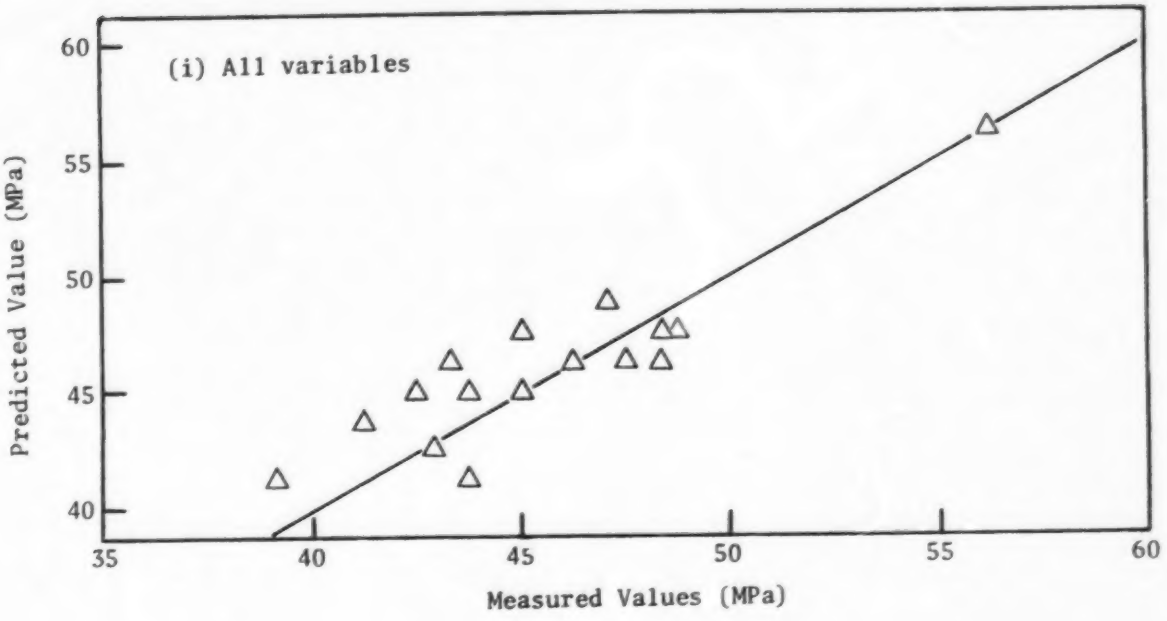


Figure 3b. Predicted and measured values of 28 day strength for 20B concrete: ——— 'ideal' line where predicted value = measured value



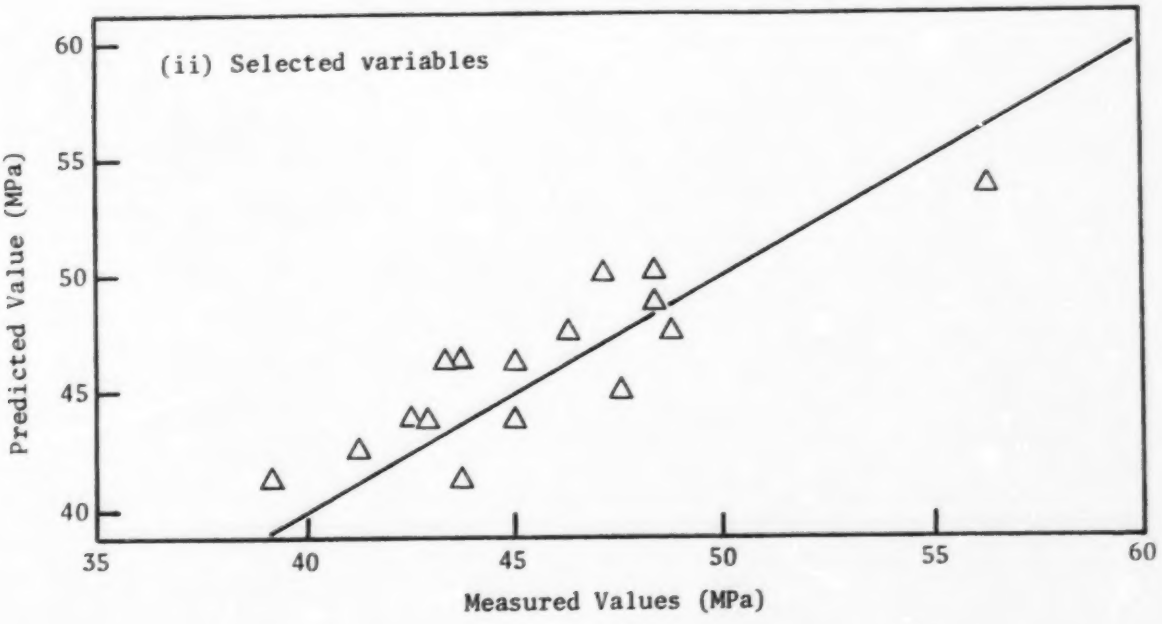


Figure 3c. Predicted and measured values of 28 day strength for 30A concrete: ——— 'ideal' line where predicted value = measured value

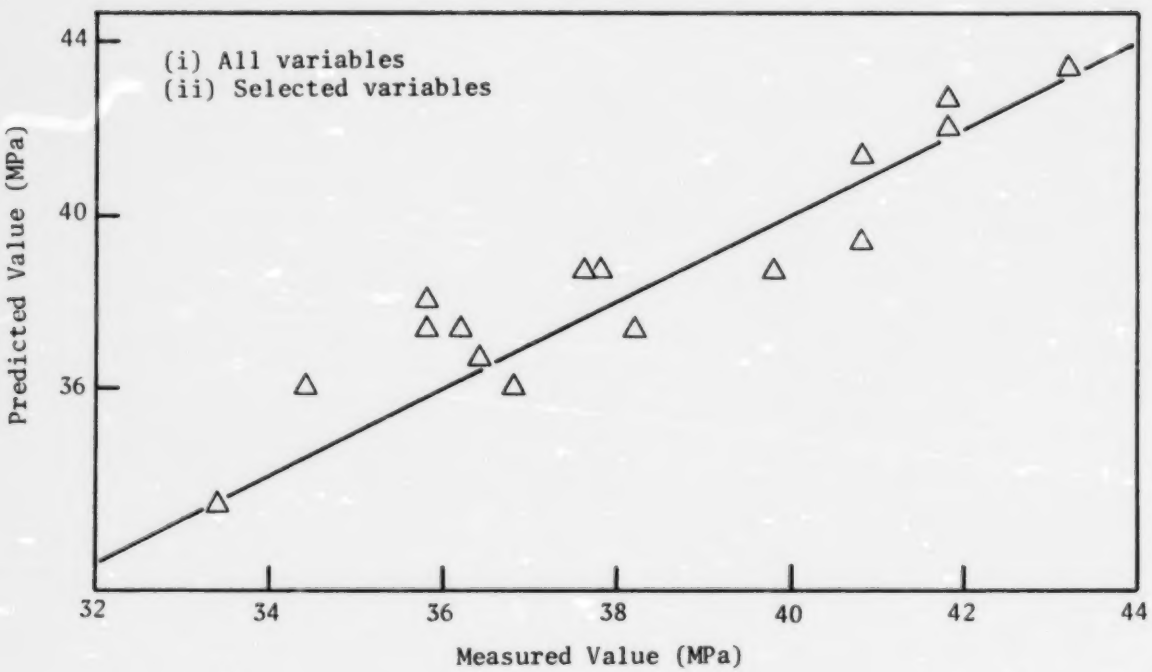
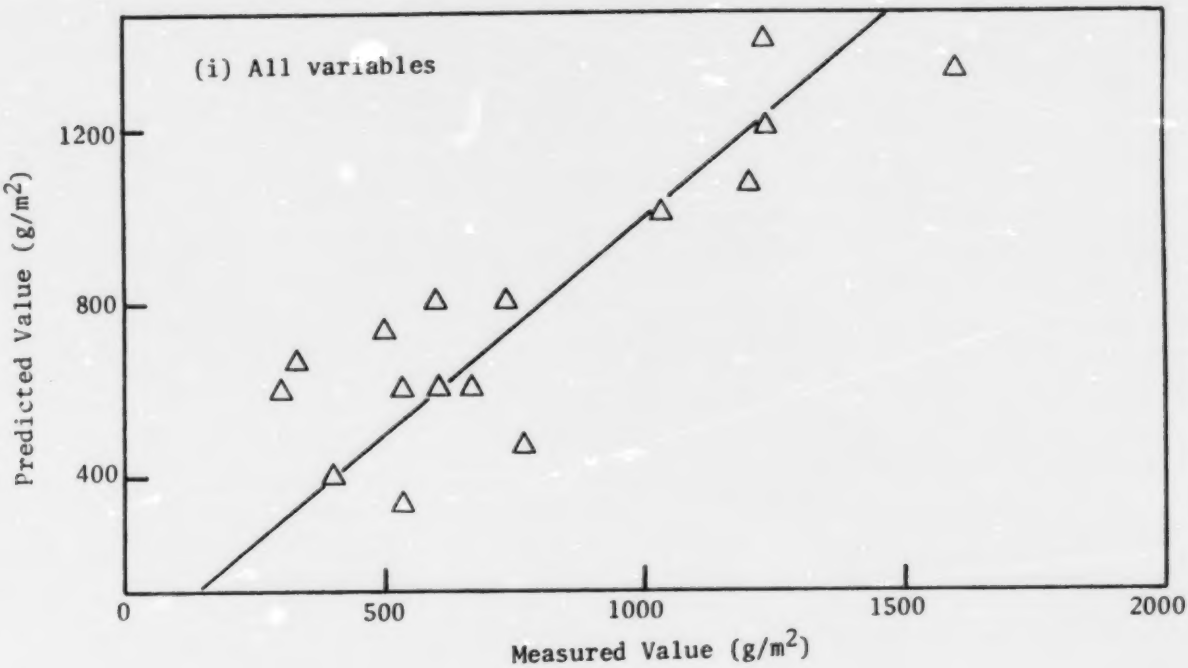


Figure 3d. Predicted and measured values of 28 day strength for 30B concrete: ——— 'ideal' line where predicted value = measured value



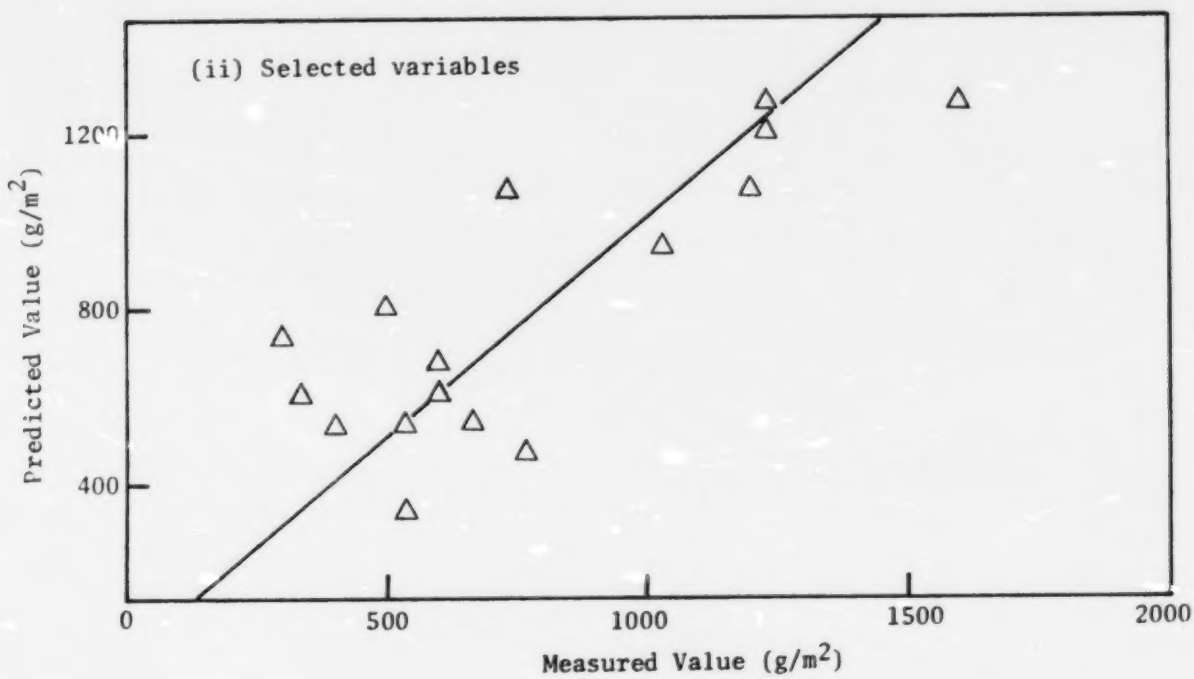


Figure 3e. Predicted and measured values of 50 cycle salt scaling loss for 20A concrete: ——— 'ideal' line where predicted value = measured value

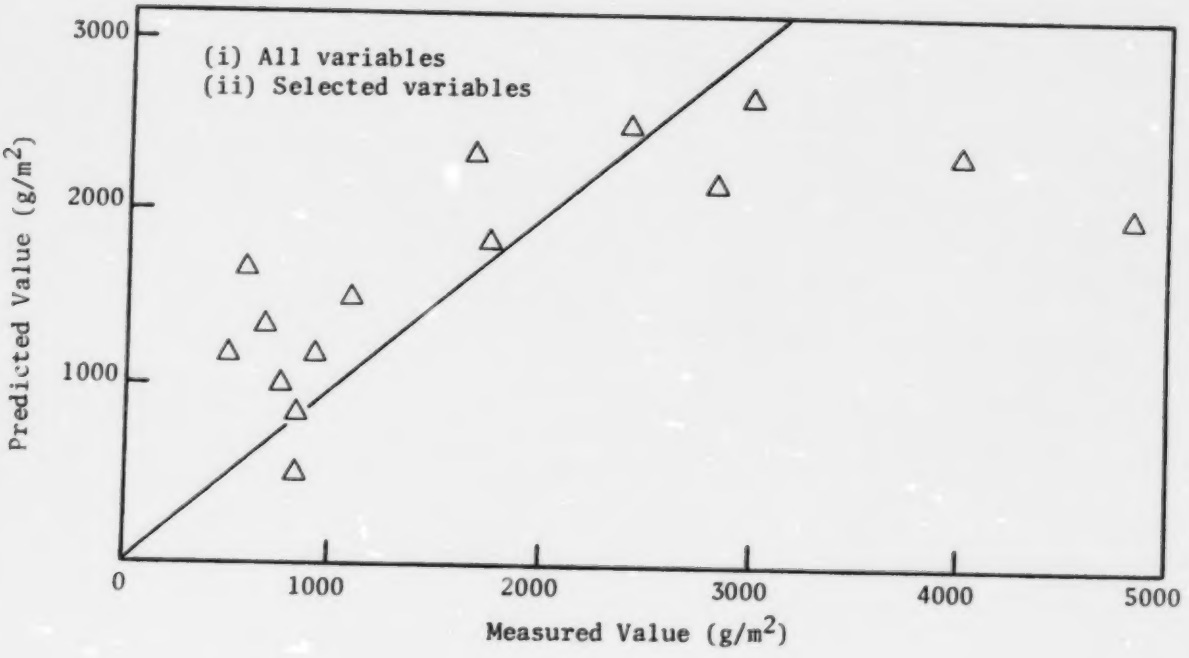


Figure 3f. Predicted and measured values of 50 cycle salt scaling loss for 20B concrete: ——— 'ideal' line where predicted value = measured value

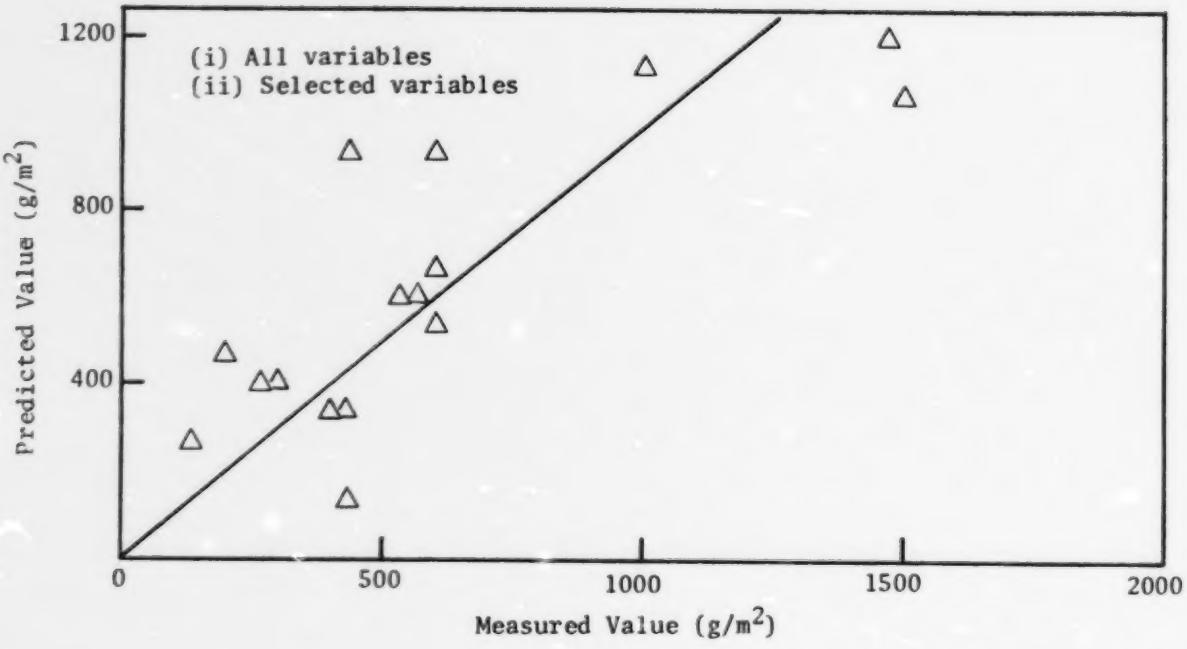


Figure 3g. Predicted and measured values of 50 cycle salt scaling loss for 30A concrete: ——— 'ideal' line where predicted value = measured value

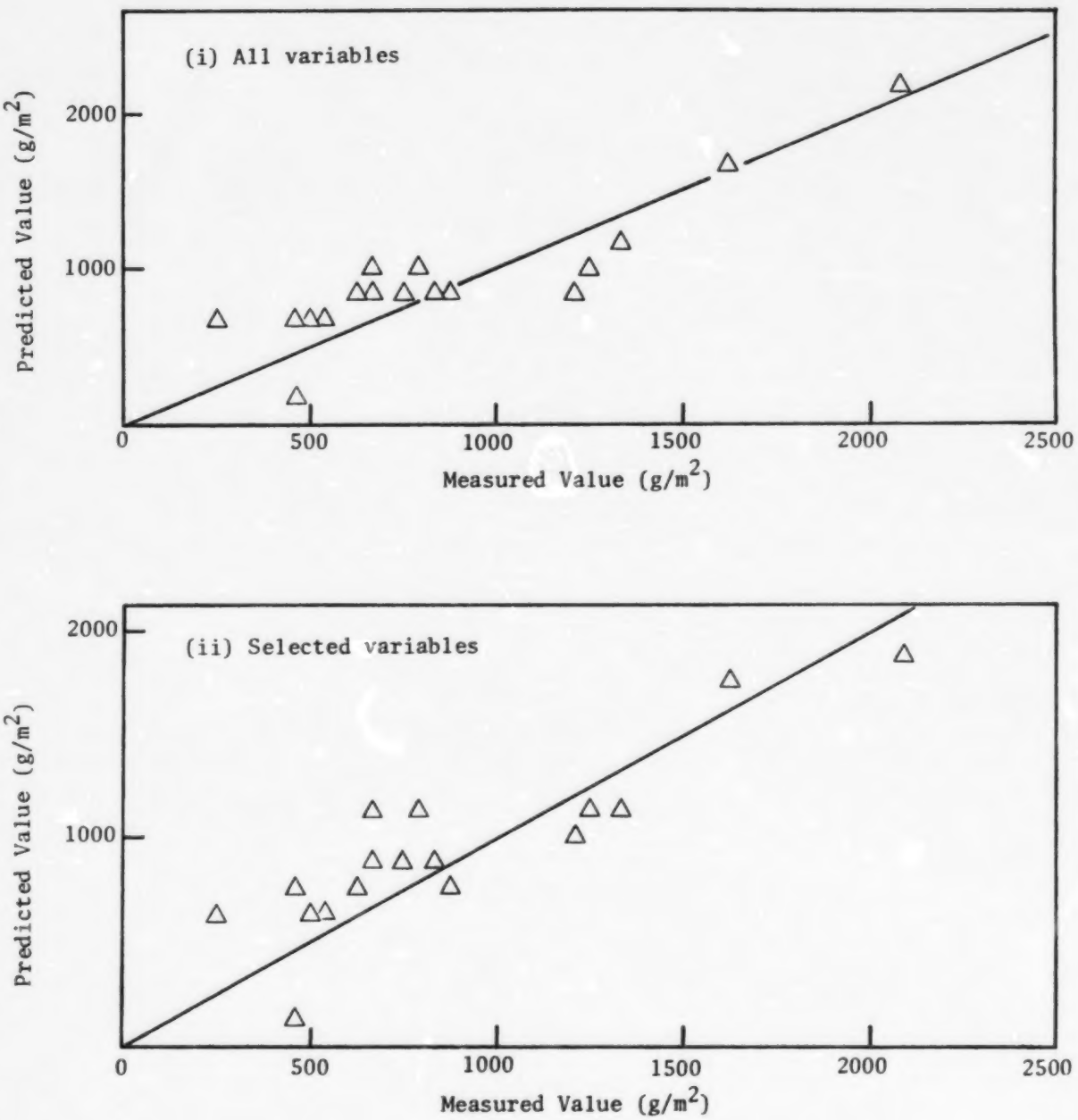


Figure 3h. Predicted and measured values of 50 cycle salt scaling loss for 30B concrete: ——— 'ideal' line where predicted value = measured value

APPENDIX

CEMENT FACTORS IDENTIFIED BY THE STATISTICAL ANALYSIS AS LIKELY INFLUENCING THE STRENGTH AND DURABILITY OF CONCRETE AND THE POSSIBLE ENGINEERING SIGNIFICANCE OF THESE FACTORS.

A.1 Strength

A study of the statistical results for the strength of the four concrete mixes indicates that relative density and set time, likely have a positive influence on strength; soundness, potassium oxide and alkali content likely have a negative influence in all four mixes. There is engineering evidence that this is not unreasonable.

A.1.1 Soundness

Soundness is primarilly related to the presence of free CaO and MgO in the cement. The CaO results from incomplete kiln reactions and the MgO results from impurities. Unfortunately the soundness test used for these cements is a function of the combined effect of these two compounds. A Le-Chatellier test would have been influenced only by the CaO and is more indicative of completeness of the kiln reactions. It is quite reasonable, therefore, that the cements with less complete kiln reactions are those which exhibit larger unsoundness expansions and which produce lower strength.

A.1.2 Set Time

Set time is related to the chemistry of the cement and is largely a function of the hydration of the aluminates. The reactivity of the C_4AF phase increases with both increasing aluminate content and a decrease in kiln temperature. Setting time also decreases with high C_3A and high SO_3 where the SO_3 is a result of addition of gypsum to the clinker. It is also known that the addition of gypsum to the raw materials lowers the required kiln burning temperature.

Sulphates from the fuel used to fire the kiln are known to influence the early reactions of the cement. High fuel SO_3 combines with the alkalis thus reducing their effect on the C_3S. Modern gas and oil have less SO_3 and thus this effect may gradually have been reduced as permissible emission is reduced.

It is reasonable, therefore, that cements which exhibit shorter set times could be those fired at lower kiln temperatures using fuels low in SO_3.

It is well known that rapid initial hydration has a detrimental effect on strength. This effect is particularly evident in hot weather concreting when it is not possible to obtain strengths developed at lower pouring temperatures. The effect is probably caused by the rapid formation of the initial calcium silicate hydrate structure and it seems that the longer this structure has to form the stronger is the cement.

A.1.3 Potassium Oxide

Potassium oxide is known to adversely influence the strength gain of cements and it is known to enter into the C_2S phase replacing some of the CaO. This either results in an increase in C_3S content or results in a greater amount of free CaO. Increased K_2O is also known to lower the required burning temperatures. Cement dust is rich in K_2O and if the

dust collected from modern precipitators is mixed with the raw ingredients this will increase the K_2O content.

A.1.4 Alkali Content

The influence of total alkali content is possibly a reflection of the increased K_2O content.

A.1.5 Relative Density

It is not known how the relative density can influence strength but it does not seem unreasonable that the higher the relative density the stronger the concrete.

A.1.6 Other Factors

It may seem surprising that the statistical analysis did not identify the traditional factors such as water-cement ratio. This is not unreasonable, however, since the concretes were all manufactured with a constant cement factor and more or less constant slump. The factors which affect strength per se could quite likely be the same factors which affect water demand for a constant slump thus eliminating the influence of water-cement ratio from the results. It must be remembered that the traditional influence of water-cement ratio refers to its effect on a single cement and not on cements with different chemical and physical characteristics.

A.1.7 Summary

The statistical results indicate that those cements which do not perform as well as others from the strength point of view are likely rich in K_2O, fired at a lower temperature and perhaps fired with low sulphate fuels. It is likely that the kiln reactions are less complete than in the superior cements.

A.2 Salt Scaling Resistance

There are no parameters which appear to influence the salt scaling resistance of all four mixes. This is perhaps not too surprising since the 20 MPa mixes are not likely to be particularly resistant with any cement. This is particularly true for mix 20B which was made with an inferior aggregate.

There are a number of parameters in the statistical analysis which are likely to influence the scaling resistance of three of the four mixes. Cement fineness, set time, Fe_2O_3 and C_4AF all have a positive influence on the scaling resistance whereas insoluble residue, C_3A, Al_2O_3 and water-cement ratio based on the cement fraction passing the 45 micron sieve all have a detrimental effect on scaling. Care must be exercised in the interpretation of these results since insoluble residue, which comes mainly from impurities in the gypsum added to the clinker, C_3A , Al_2O_3, Fe_2O_3 and C_4AF are all interrelated. The insoluble residue is a function of the amount of C_3A and the amount of C_3A is related to the Al_2O_3 in the cement. Fe_2O_3 on the other hand reduces the amount of C_3A formed and increases the amount of C_4AF. Thus the effect of all these parameters may be simply a manifestation of the quantity of C_3A or the amount of gypsum added to the clinker.

A.2.1 Cement Fineness

The most consistent parameter indicated by the statistical analysis for the salt scaling resistance is the amount of the very fine particles in the cement. Indeed, the amount finer than 10 microns is consistently indicated as important. From the engineering point of view, however, it seems more practical to consider the amount of cement finer than, for example, 20 microns since this is a larger fraction of the whole and experimental deviations in the measured quantities are likely to be smaller.

This influence of the very fine particles could possibly be attributed to the early strength gain of the concrete. Certainly if the saturation of the water in the mix with silicates is associated with the hardening process then the very fine particles will have an influence because of their very large surface area.

A.2.2 Set Time

As for the strength analysis the statistical analysis indicates that the longer the set time the more likely the cement will produce a concrete with superior salt scaling resistance. Again it is probable that this could be a result of the superior structure formed by the hydrating cement if this initial structure is formed slowly.

A.2.3 Tricalcium Aluminate Content and Related Parameters

Higher C_3A contents result in faster set times since, as explained above, it is primarily the aluminates which dictate set times. C_3A is also known to react with the chloride ion to form tricalcium chloroaluminate. Whether this has an influence on salt scaling resistance is not known.

A.2.4 Summary

The statistical analysis indicates that a cement which produces concrete with superior salt scaling resistance is one which contains a relatively high proportion of very fine particles, is low in C_3A content and exhibits a slow set time.